NUMERICAL MODELLING OF THE EVOLUTION OF MONSOON CIRCULATION ALONG 80°E

George William Schwenke

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

NUMERICAL MODELLING OF THE EVOLUTION
OF MONSOON CIRCULATION ALONG 80°E

by

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March 1977

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Numerical Modelling of the Evolution of Monsoon Circulation Along 80°E

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

The UCLA general circulation model developed by Arakawa and Mintz (1975) was used to study the evolution of the northern summer monsoon during a 180 day period commencing in mid January. The global model, modified to a five degree latitude by five degree longitude grid resolution, was run for five vertical levels in a zonally symmetric mode along 80° E to permit the extended computational period. Thermal forcing was simulated by continuously adjusting computed temperatures at each level toward the radiative equilibrium temperature for that level as estimated by Palmén and Newton (1967). These equilibrium temperatures were also adjusted during the 180 day period from the January mean to the July mean. The evolution and location of the major zonal components of the monsoon were reasonably simulated. The results indicate that a zonally symmetric model is suitable for studies on the planetary-scale features of the monsoon with the realization that exclusion of zonally-asymmetric phenomena from such a model limits its accuracy and usefulness in considering the effects of such events on the monsoon system.

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I. INTRODUCTION

The monsoon circulation has long been the subject of conjecture and analysis by meteorologists because of its planetary scale and its environmental effects on almost half the world's population. While for many people the word "monsoon" is synonymous with the occurrence of heavy seasonal rainfall over India and portions of southeast Asia, this event is but one component of the total monsoon, which extends its influence from the surface to the stratosphere over one third of the globe.

Krishnamurti and Bhalme (1976) defined the broad scale monsoon system in terms of several parameters which include: (1) the monsoon trough, (2) the Mascarene sub-tropical high, (3) the low-level cross equatorial jet, (4) the Tibetan high, (5) the tropical upper-tropospheric easterly jet and (6) the monsoon rainfall. The principal time-mean circulation features of the northern hemisphere summer monsoon have been known and understood for some time, but detailed synoptic analysis and accurate numerical simulation are frequently hindered by the lack of meteorological data, especially for upper air levels.

The monsoon develops over southeast Asia as a whole, extending roughly from 60°E to 120°E. The reversal of flow pattern between seasons is most intense and persistent over India and extreme southeast Asia. These regions plus the

Tibetan plateau in southwestern China may be viewed as the most active areas for the summer monsoon. The two components which affect upper levels in these areas most directly are the Tibetan high and the Indian jet. The Tibetan high is a warm core high whose formation is thought to be related to the thermal and mechanical effects of the Tibetan highland. Latent heat release due to shallow and deep cumulus convection appears to play an important role in the maintenance of the upper anticyclone.

The easterly upper-tropospheric jet near 150 mb is another interesting feature of the monsoon system. This jet has winds of roughly 80 to 100 kts with the strongest winds being found just to the west of the southern tip of India over the Arabian Sea. The jet forms in the monsoon month of June and is usually present until September. The proper simulation of these two related components of the monsoon system by a given numerical model is frequently considered to be a prerequisite for further application of the model to monsoon studies.

The observed circulation systems and the theories proposed for their existence have generated numerous synoptic and numerical studies of the monsoon circulation. The numerical models have ranged from simple barotropic regional models to complex global general circulation models (GCM).

Holton and Colton (1972) used a simple linear one-level barotropic vorticity equation with the observed 200-mb seasonal mean divergence as the forcing to successfully simulate

the seasonal mean flow pattern. They found, however, that an extraordinarily large friction was needed to damp the vorticity generation and keep the field in phase with the forcing function. Bellis (1975) and Pentimontti (1976) used a multi-level model formulated by Monaco and Williams (1975). This model was essentially similar to the UCLA general circulation model in use at that time except that parameterization of sub grid-scale processes and separate calculations for boundary layer terms were not included. The model fairly accurately simulated the observed monsoon features except that phase shift problems were also noted. Hahn and Manabe (1973) and Washington and Daggupath (1975) have demonstrated the ability of the complex GCM, which includes parameterized heating and topography, to successfully simulate the northern summer monsoon. These complex GCM's have some distinct disadvantages in their application to monsoon studies because the large geographical domains monsoon simulations require, coupled with the complexity of the physics in these models, result in vast computational time and computer core requirements.

In an attempt to incorporate the improved vertical resolution and surface terrain representation found in the GCM into a more tractable model for monsoon studies, Murakami (1969) noted that the main characteristics of the monsoon circulation are practically the same along a given latitude over the area between roughly 60°E to 120°E. The geography of this area is relatively uniform in that it consists of a

land mass to the north and oceans to the south. He thus concluded that one could introduce an idealized numerical model using a two-dimensional vertical plane along 80°E from the equator to the north pole. This model thus considers only the meridional circulation and its associated zonal current and allows no disturbances to be superimposed upon the zonal motion. Murakami developed a nine level zonally-symmetric model which included as dependent variables horizontal and vertical velocity components, pressure, temperature and a moisture variable. Sea surface temperature was prescribed south of 10°N with land to the north where smoothed topography was included. Two factors which were disregarded in this model were the seasonal variation of the monsoon circulation and the interaction between the northern and southern hemispheres. The model was started from an atmosphere at rest and reached a statistical steady-state after 80 days.

Murakami found that a zonally-symmetric model could accurately simulate many of the well known broad-scale features of the monsoon, including (1) low-level southwesterly flow between the equator and about 30°N, (2) the upper-level anticyclone and (3) a pronounced easterly jet near 150 mb on the southern boundary of the upper-level anticyclone.

It is the intent of this study to evaluate the effectiveness and accuracy of the UCLA GCM as developed by Arakawa and Mintz (1975) in a zonally-symmetric mode along 80°E. This study will differ from the model developed by Murakami in that the UCLA GCM incorporates parameterized heating and

cumulus convection and a pole-to-pole geographical domain. Additionally, improvements in computer systems have increased computational speed to the extent that it is possible to initialize the model to the observed January zonally-averaged temperatures with the atmosphere at rest, let the model attain steady-state and then integrate in time for 180 days while simultaneously adjusting the zonally-averaged equilibrium temperatures from January to July.

II. DESCRIPTION OF THE NUMERICAL MODEL

A. BASIC MODEL

The UCLA general circulation model, developed by Arakawa and Mintz (1975) and modified by Arakawa and Lamb (1976) was used as the basic model. The primary prognostic variables are horizontal velocity, temperature and surface pressure, governed, respectively, by the horizontal momentum equation, the thermodynamic energy equation and the surface pressure tendency equation. In this study the model was run for a vertical plane extending from 90° N to 90° S along 80°E with five "sigma" levels as the vertical coordinates in the spherical coordinate model. Cyclic continuity was maintained on either side of the primary 80°E vertical plane, with computations at the poles stabilized by the zonal symmetry of the model.

B. THE GRID SYSTEM

In the vertical the model was run with five sigma levels (σ = .9, .7, .5, .3, and .15) interpolated to constant pressure surfaces of 900, 700, 500, 300 and 150 mb. The sigma coordinate is defined as

$$\sigma \equiv \frac{p - p_t}{\pi} \qquad (2.1)$$

where p is the pressure of the sigma level, p_t is the constant tropopause height which was set to 100 mb, and π is the "terrain pressure" defined as

$$\pi \equiv p_s - p_t \qquad (2.2)$$

The surface pressure, p_s, is set to 1000 mb initially. From (2.1) it follows that

$$\sigma = 0 \text{ at } p = p_t$$

$$\sigma = 1 \text{ at } p = p_s$$

which are the vertical boundaries of the model. The boundary conditions at $\sigma = 1$ and $\sigma = 0$ are both $\frac{d\sigma}{dt} = 0$.

The horizontal distribution of variables is illustrated in Figure 2. The grid points are spaced every five degrees in latitude. Values of v, calculated for implicit points to the north and south of the (i,j) point, are averaged to obtain a value for the (i,j) point. The implicit u values are equal due to the zonal symmetry of the model as used in this study.

C. PARAMETERIZATION OF SUB GRID-SCALE PROPERTIES

A model of the interaction of a cumulus cloud ensemble with the large-scale environment, as developed by Arakawa and Schubert (1974), is applied in the UCLA GCM used in this study.

In the model, the large scale environment is divided into the subcloud layer and the region above. The time changes of the environment are governed by the heat and moisture budget equations for the subcloud mixed layer and the region above, and by a prognostic equation for the depth of the mixed layer. In the environment above the mixed layer, cumulus convection affects the temperature and moisture fields through cumulus-induced subsidence and the detrainment from the cumulus clouds of saturated air containing liquid water, which evaporates into the environment. In the subcloud mixed layer, cumulus convection does not act directly upon the temperature and moisture fields, but it affects the depth of the mixed layer through the cumulus-induced subsidence.

D. DIABATIC HEATING

The UCLA model is designed to use a detailed solar radiation balance routine to calculate the net diabatic heating. This radiation subroutine calculates incoming short wave radiation as a function of solar zenith angle and computes such factors as reflection from clouds, re-radiation from the surface and the effects of moisture on this long wave

radiation. However, this routine is very time consuming and thus was not used in this 180 day study. In this zonally-symmetric application of the model, the forcing function is the zonally symmetric observed thermal gradient, or equilibrium temperature T*. These temperatures, taken from the observations given by Palmén and Newton (1967) are used in the following formula to calculate the heating component:

$$Q = -\left[\frac{T - T^*\ (y, \sigma)}{\tau}\right]$$

In this adjustment formula T is the computed temperature for the given latitude and sigma level; T* the equilibrium temperature for this same point, and τ a specified adjustment time taken as two days in this study. The T* field is adjusted each hour during the 180 day computational period to reflect the seasonal temperature change from January to July while maintaining the north-south temperature gradient. Figures 3a and 3b detail the T* fields for January and July, respectively. A linear interpolation is used to determine the hourly adjustment applied to the January field during the 180 day period to increment it to the July values at the end of the period.

E. INTEGRATION SCHEME AND INITIAL CONDITIONS

The time integration is comprised of continuous sections of 1 Matsuno (Euler Backward) step and 4 leap frog steps. The model was initialized to the January zonally-symmetric

equilibrium temperatures (T*) and specific humidity. Initial sea surface and surface temperatures for 80°E were estimated from the global data prepared by Schultz and Gates (1972) for January. The model was run with a 5°-resolved smoothed topography derived from the actual topography along 80°E. The model was integrated for 60 days to bring it into equilibrium with the January T* fields, and was then run for the 180-day period of study while the T* fields were changed to simulate the seasonal radiation changes. All fields were interpolated to five constant pressure surfaces of 150 mb, 300 mb, 500 mb, 700 mb and 900 mb.

III. RESULTS

The evolution and location of the major zonal components of the monsoon were reasonably simulated by the model in this study.

Figure 5a shows the calculated u component field for January. This field is the resultant of the 60 day integration during which the model reached a steady wind state with the January equilibrium temperatures. The calculated field shows a maximum of approximately +18 m sec^{-1} at 150 mb in the northern hemisphere mid-latitudes, with a broad, weaker area of upper westerlies in the southern hemisphere. A maximum in the easterly wind is noted in the tropical southern hemisphere, reflecting the trade winds. The January temperature field, shown in Figure 6a, closely resembles the January equilibrium temperature, as expected, except that the

calculated temperatures in the tropics appear to be slightly cooler than the equilibrium temperatures.

During the next thirty days, from day 1 to day 30, the gradual change in equilibrium temperatures was begun. By day 30, the u component field (Figure 5b) showed a slight decrease in the intensity of the northern hemisphere upper westerlies, with little change elsewhere in the hemisphere. The temperature field for day 30, shown in Figure 6b, indicates a fairly significant lower-level warming in the northern middle and high latitudes, with only slight cooling in the southern hemisphere.

The next sixty days of integration, from day 30 to day 90 (mid February to mid April), showed the onset of a significant positive u component near 10°N latitude. Figures 5c and 5d detail these fields. The v components in this area were also observed to be positive, implying a southwest low-level flow. Additionally, around day 75, an area of upper-tropospheric easterly winds is noted at about 10°N from 200 mb to 400 mb. This feature appeared during the ten day interval (the interval for which data was saved during the run) between day 70 and day 80. The northern upper level westerlies continued to weaken slightly during this sixty day period, and the temperature fields (Figures 6c and 6d) indicate continued northern hemisphere lower level warming, with the 900 mb freezing level extending up to latitude 63°N by day 90 (mid April).

The period from mid April (day 90) to mid June (day 150) shows a continued intensification in both the low level south

westerly flow near 15°N and the upper level easterly flow near 10°N from approximately 150 mb to 500 mb. A bi-modal lower level easterly wind maximum is noted in the southern hemisphere tropics near 10° S and 26°S by mid June. This feature first appears in April as a single maximum near 28°S, with the two maxima developing in May. The southern hemisphere westerlies intensified and moved northward to about 30°S by day 150 (June) with maximum amplitudes on the order of 19 m sec^{-1}.

The temperature fields for days 90 to 150, as shown in Figures 6d through 6f, indicate continued northern hemisphere warming and southern hemisphere cooling.

The last thirty days of integration, from day 150 to day 180, represent the northern summer monsoon circulation as simulated by the zonally symmetric model. The southwest low-level flow is quite well developed, with a maximum amplitude of 19 m sec^{-1} near 14°N. The easterly jet is also evident, with a maximum value of about 10 m sec^{-1} near 15°N at 150 mb. The northern hemisphere westerlies are displaced to near 55° N, with values of 10 m sec^{-1} at 350 mb, while southern hemisphere westerlies in excess of 20 m sec^{-1} are located near 300 mb at 25°S.

Temperatures for day 180, as shown in Figure 6g, are in excess of 20 °C at 900 mb for northern hemisphere land areas south of 54 N. These are warmer by 3 to 7° C than the equilibrium temperatures for these areas, and this is perhaps a result of the cumulus parameterization affecting the calculated temperatures by warming the lower and middle troposphere.

IV. CONCLUSIONS

The zonally symmetric model appears to be suitable for a wide range of studies on the monsoon and its evolution in time. In this study, the major zonally symmetric features of the monsoon, such as the tropical upper-tropospheric easterly jet and the low-level southwesterly flow regime, were accurately simulated in position. The magnitudes of these features were not so accurately simulated, however, as the upper level easterlies and westerlies tended to be under-predicted and the low-level flow appeared to be over-predicted. Figure 4 shows the observed magnitudes of these features during July 1967; the easterly jet has winds in excess of 30 m sec^{-1} while this zonally symmetric simulation produced winds of only about 10 m sec^{-1}. This problem appears to be related to the thermal forcing used in this simulation. The zonally-averaged equilibrium temperatures, used in this study as the mean thermal gradient and the forcing function for major zonal circulation systems, are not representative of the more intense gradients which exist over Asia. As such, the use of these T* fields should and did result in weaker gradients over the monsoon area and thus weaker zonal circulation patterns in both easterly and westerly flow.

The excessive magnitude of the low-level southwesterly flow is not so easily understood. The observed magnitude is approximately 10 m sec^{-1}; while the zonally symmetric model

indicates values of nearly 20 m sec^{-1}. The discrepancy may be a result of the high topography to the north and its effects on the calculation of lower level thermal gradients, as well as its effects on cumulus parameterization and planetary boundary layer parameters.

Future work with zonally symmetric models might center around one of the following changes to this study:

(1) Increase the vertical resolution of the model from the present five tropospheric levels to nine or more.

(2) Use an equilibrium temperature (T*) field which more accurately reflects the true gradients along the longitude under study.

(3) Use the actual radiation subroutine as the thermal forcing rather than equilibrium temperature fields.

(4) Evaluate the effects of southern hemisphere sea surface temperatures on the northern summer monsoon.

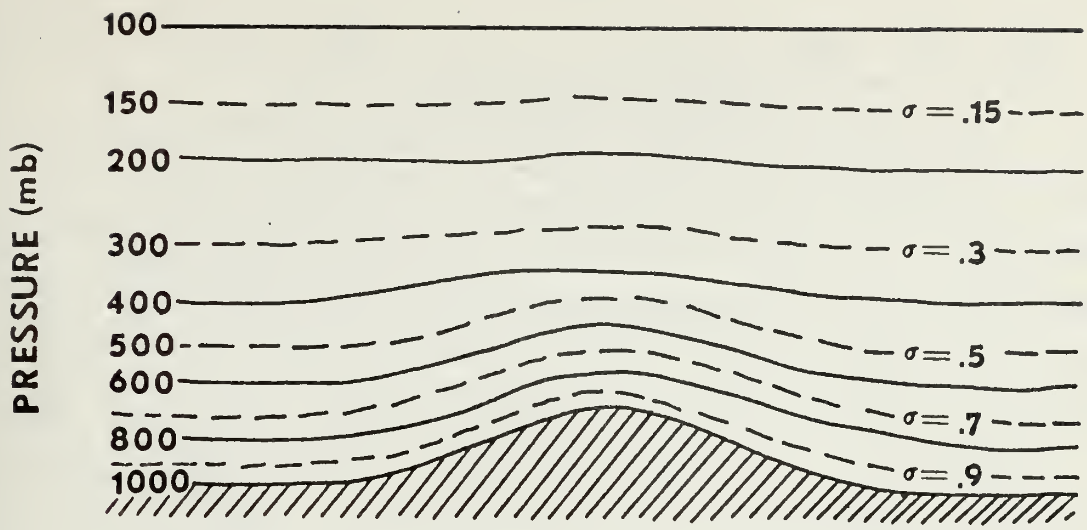

Figure 1. Vertical levels: Sigma (σ) is the vertical coordinate. Values for horizontal velocity components, geopotential and temperature are carried at the five sigma levels (dashed lines). Values for terrain pressure (π) and vertical motion $\left(\frac{\partial\sigma}{\partial t}\right)$ are calculated on solid line pressure surfaces.

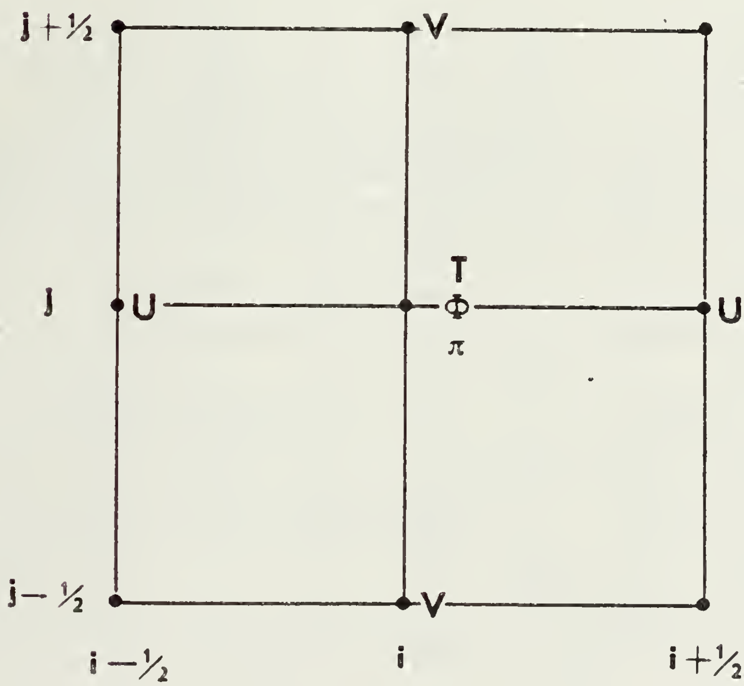

Figure 2. The horizontal distribution of dependent variables around a given (i,j) grid point.

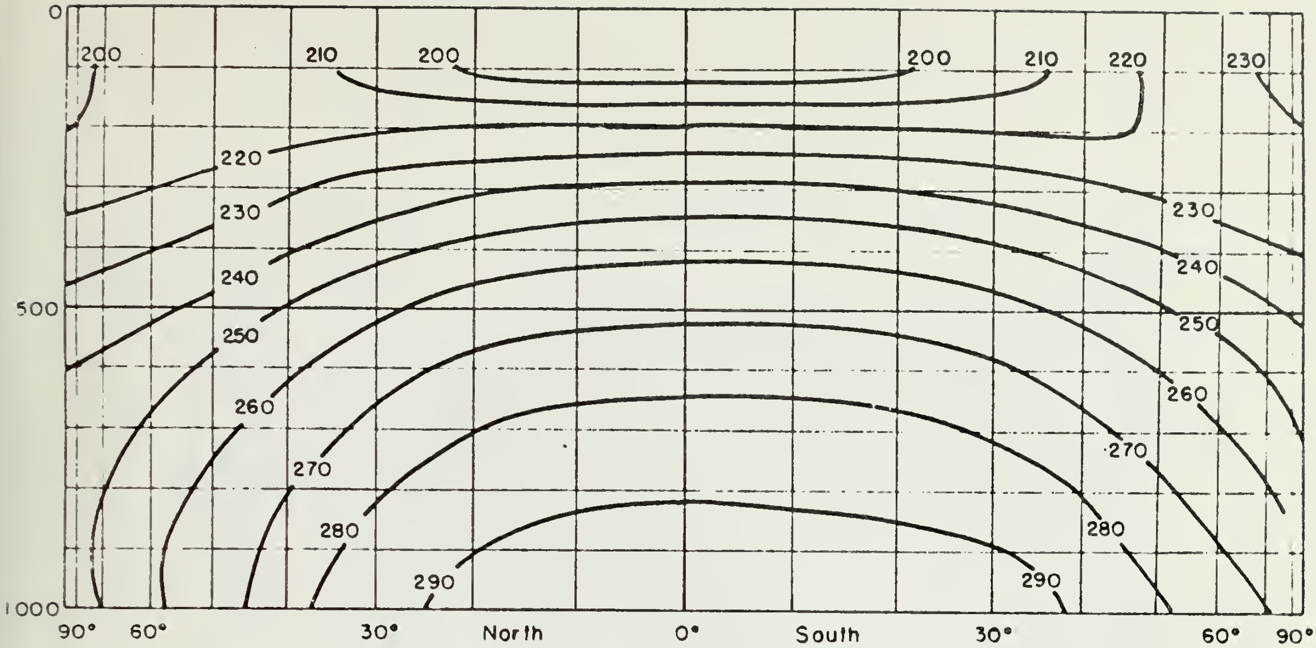

Figure 3a. The time-and-longitude averaged temperature (T) in January as estimated by Palmén and Newton (1969). Values are in degrees K.

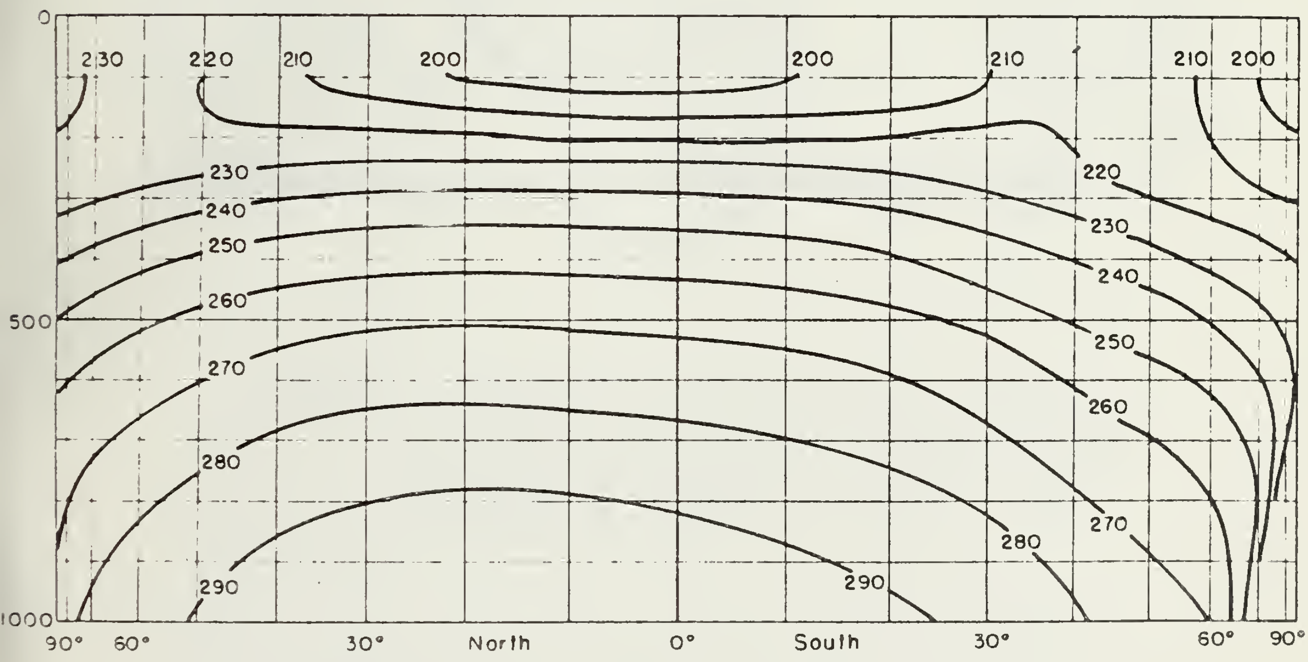

Figure 3b. The time-and-longitude averaged temperature ($\bar{T}$) in July as estimated by Palmén and Newton (1969). Values are in degrees K.

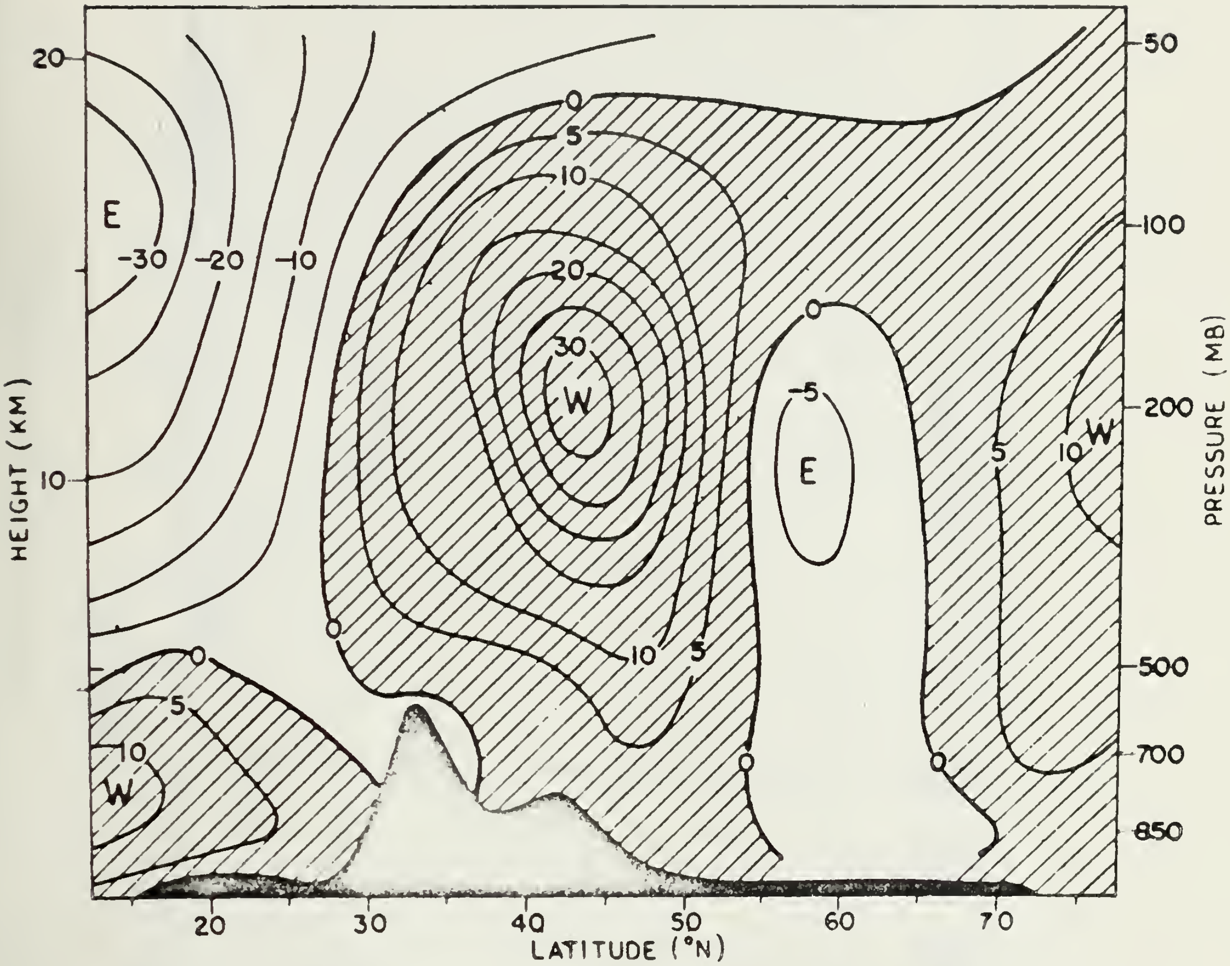

Figure 4. The Northern hemisphere monthly mean zonal geostrophic wind along 80°E in July 1967. Isolines are for 5 m sec^{-1} intervals; hatching indicates positive u component. Taken from Murakami (1969).

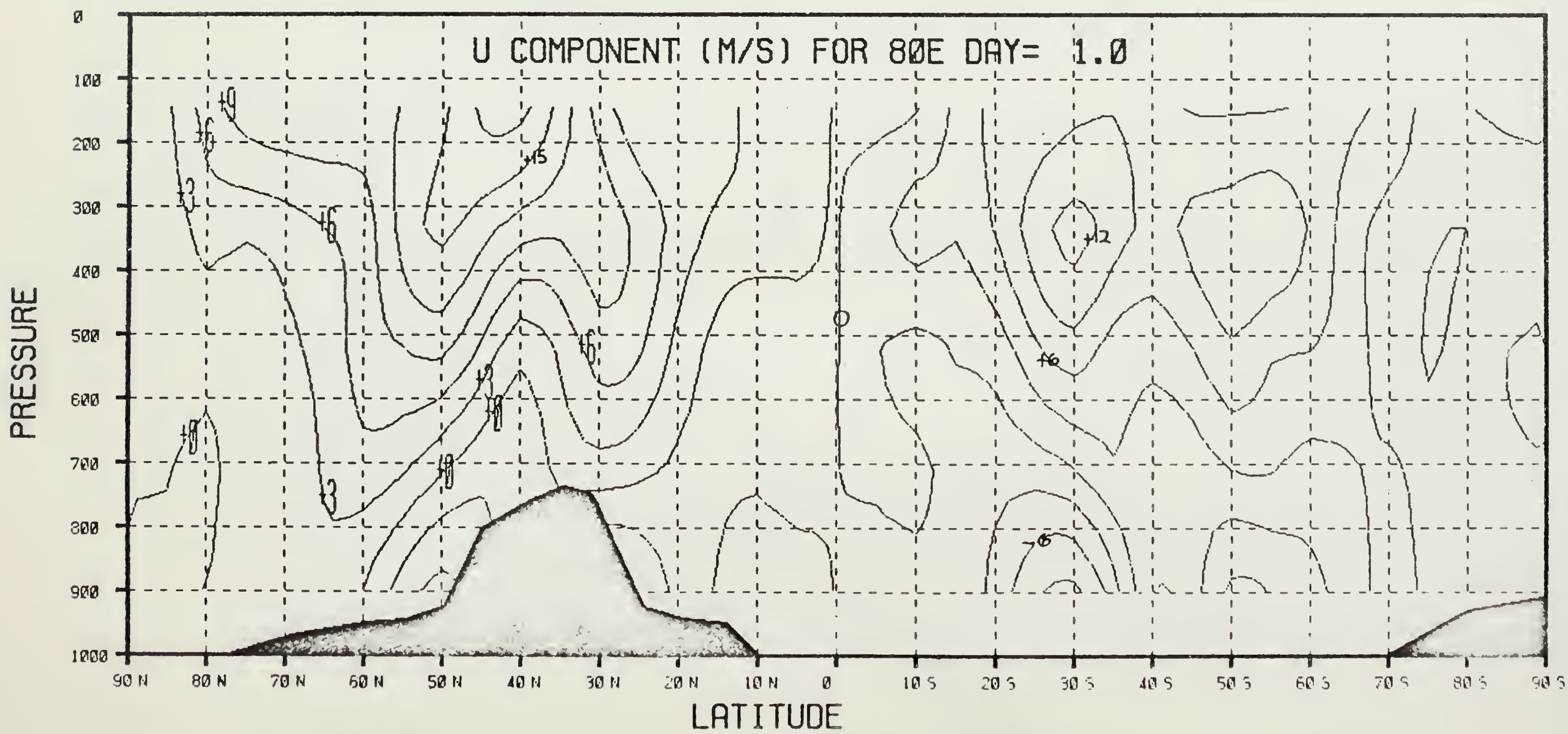

Figure 5a. Zonal u component for day 1 (January)

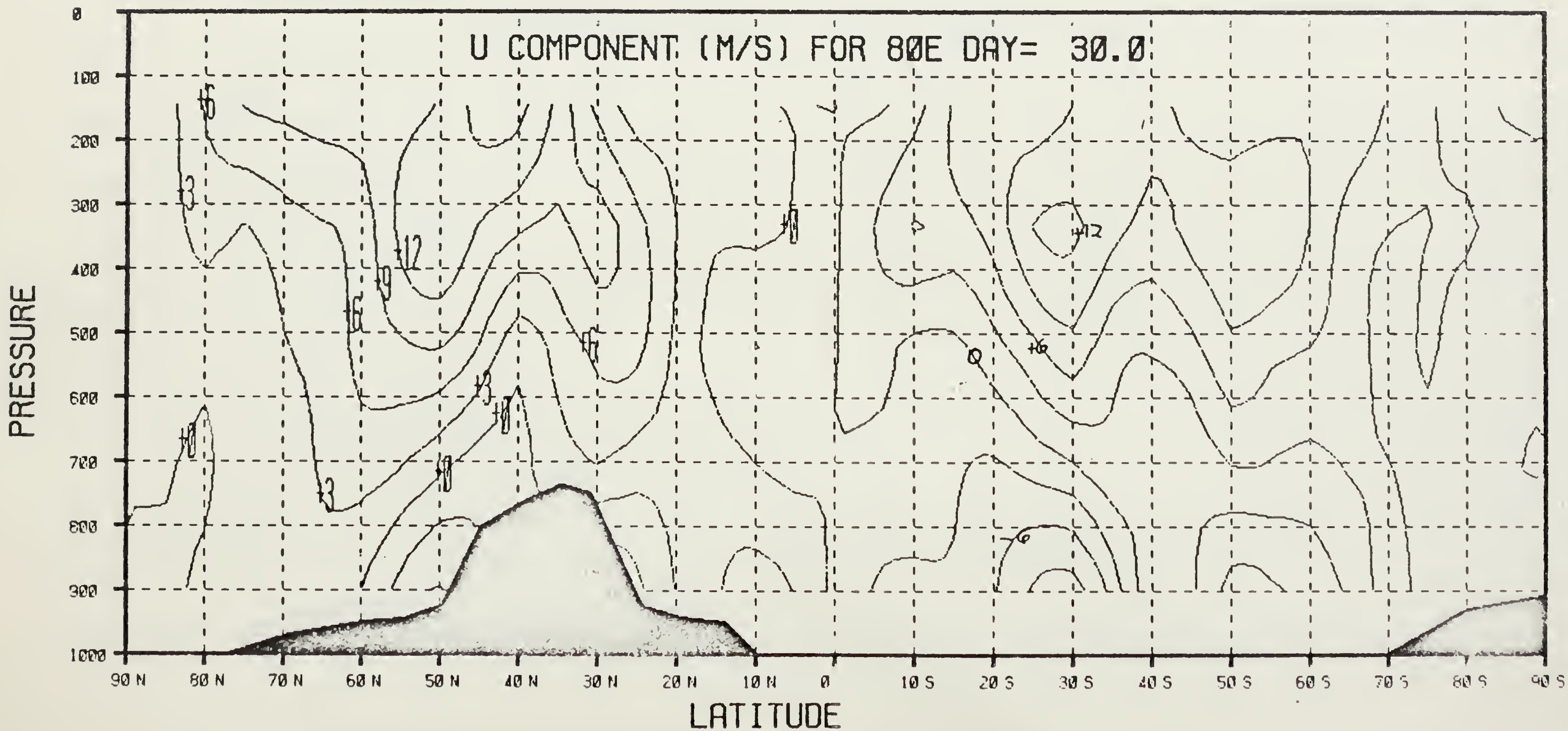

Figure 5b. Zonal u component for day 30 (February)

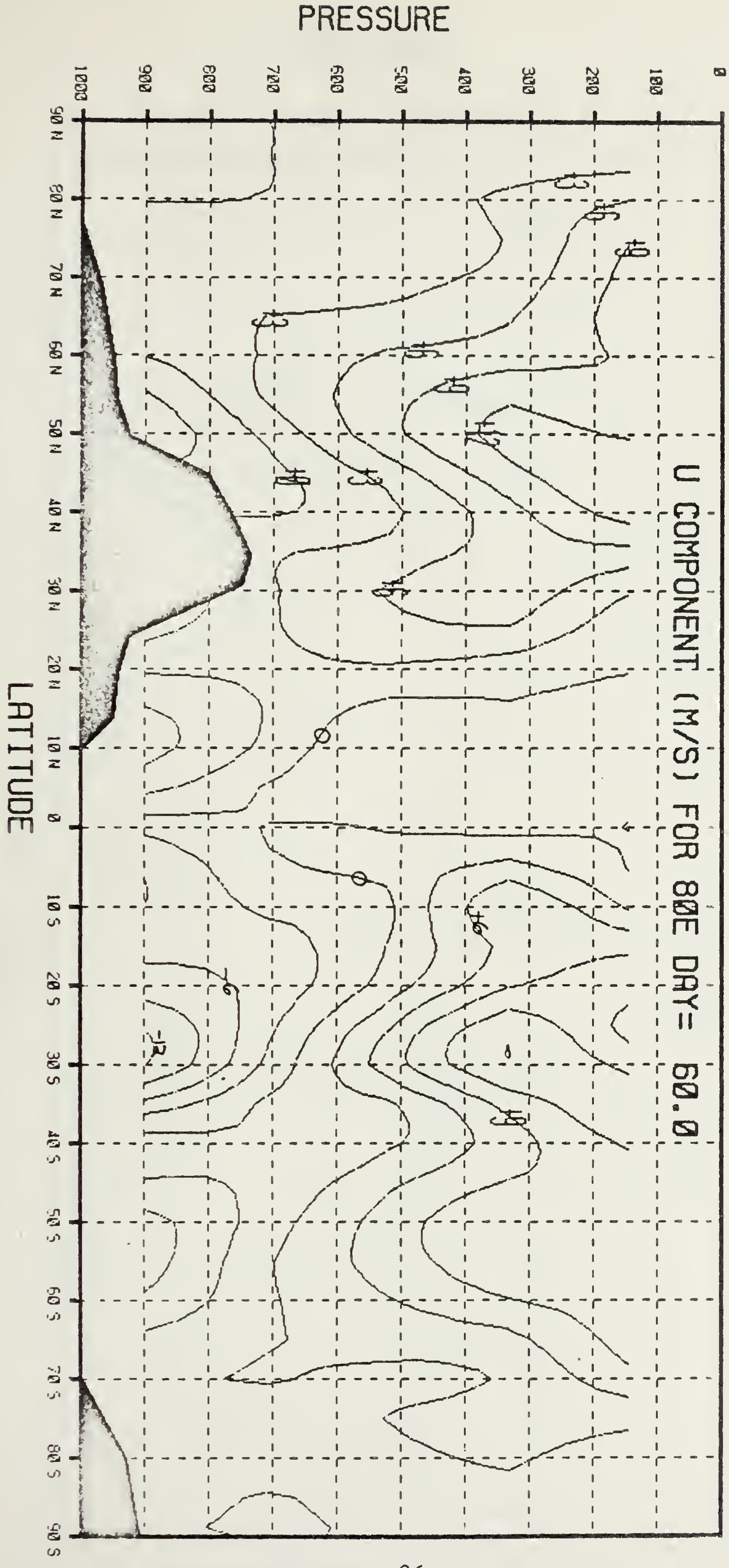

Figure 5c. Zonal u component for day 60 (March)

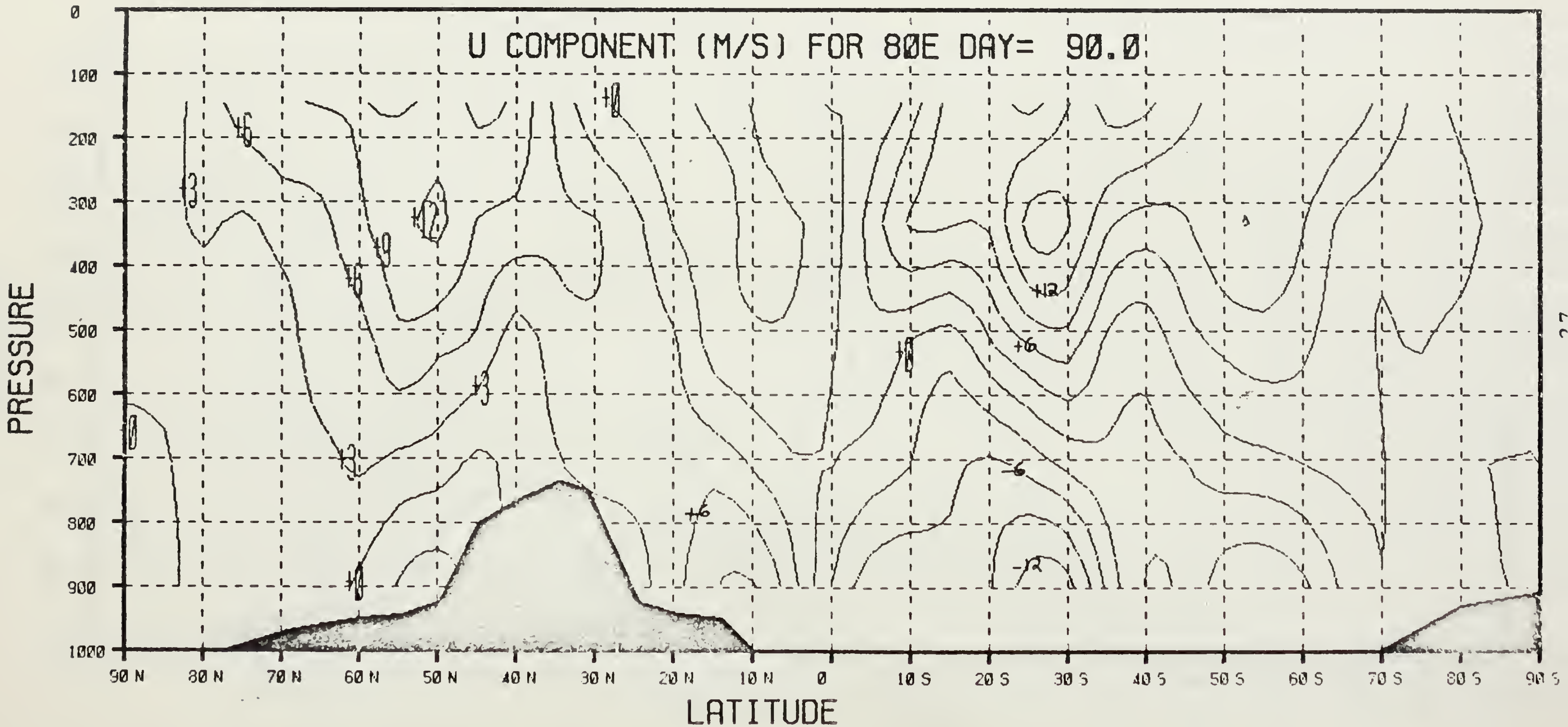

Figure 5d. Zonal u component for day 90 (April).

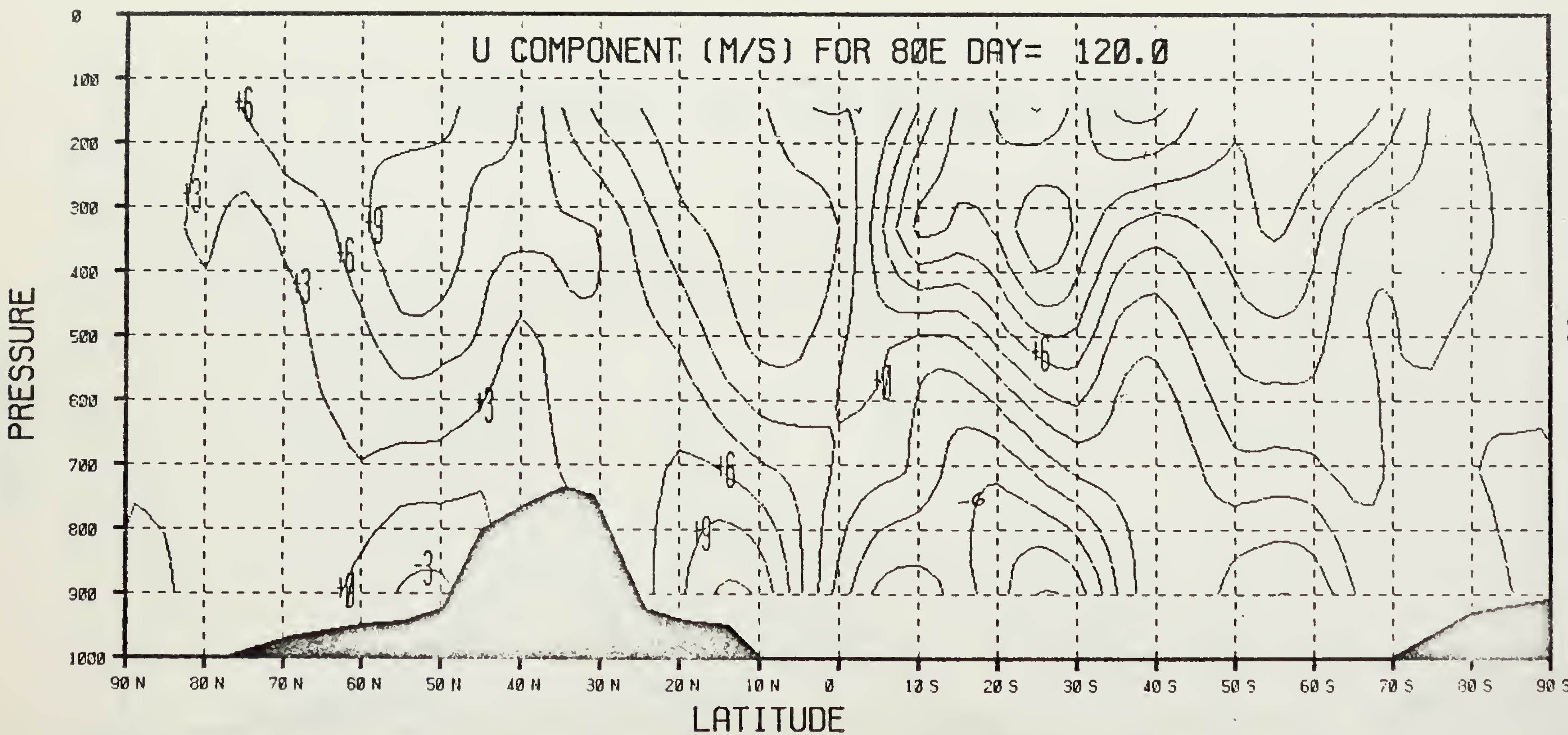

Figure 5e. Zonal u component for day 120 (May)

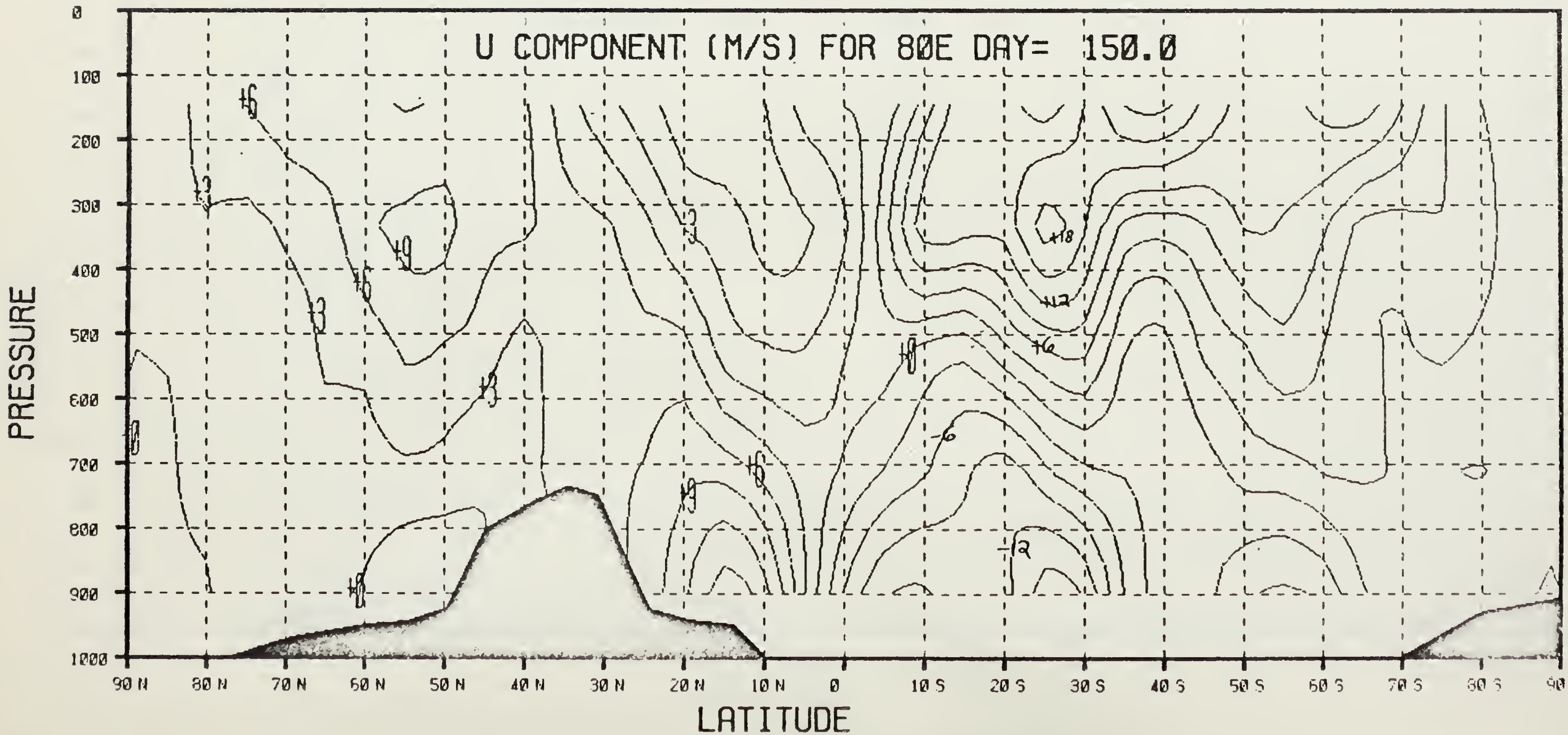

Figure 5f. Zonal u component for day 150 (June)

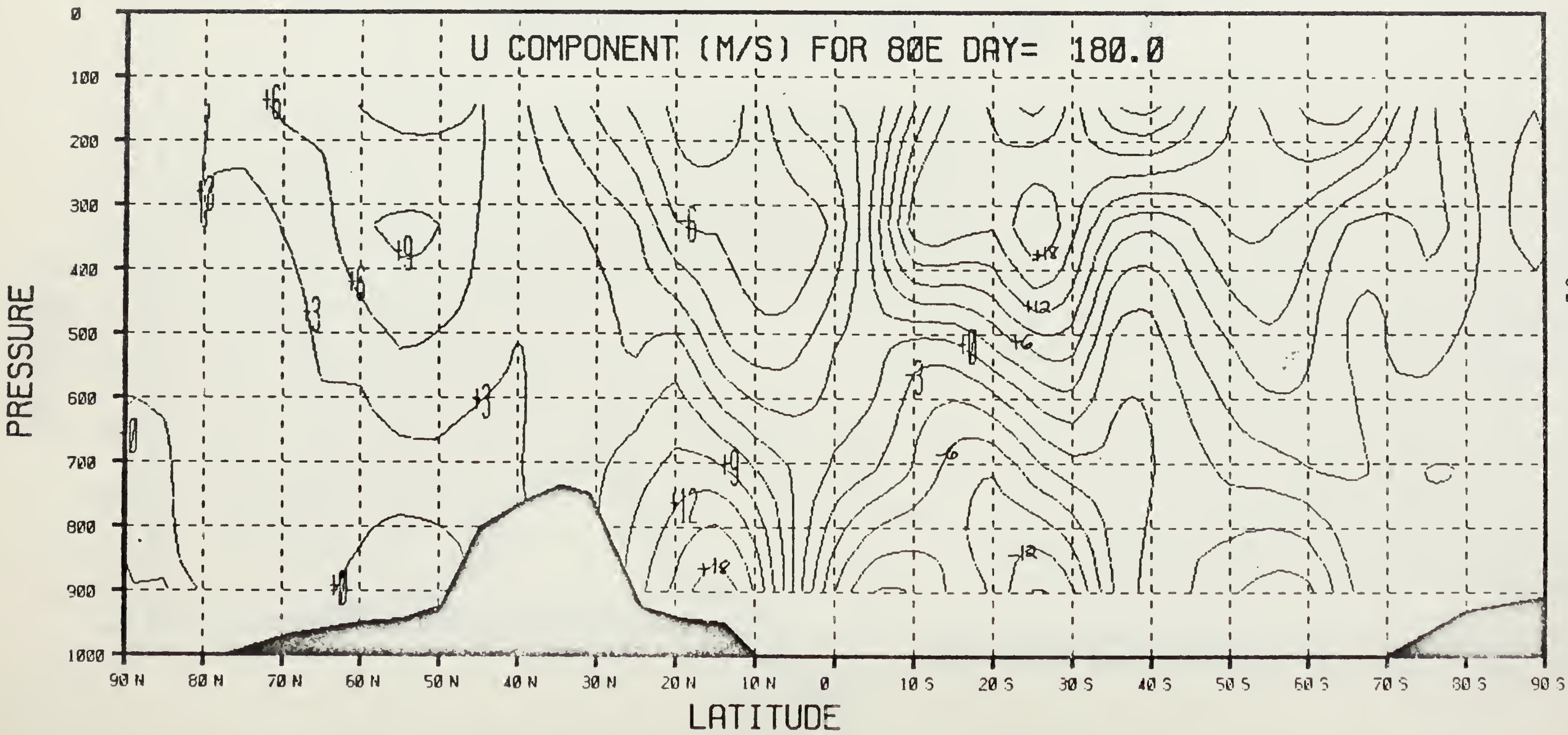

Figure 5g. Zonal u component for day 180 (July)

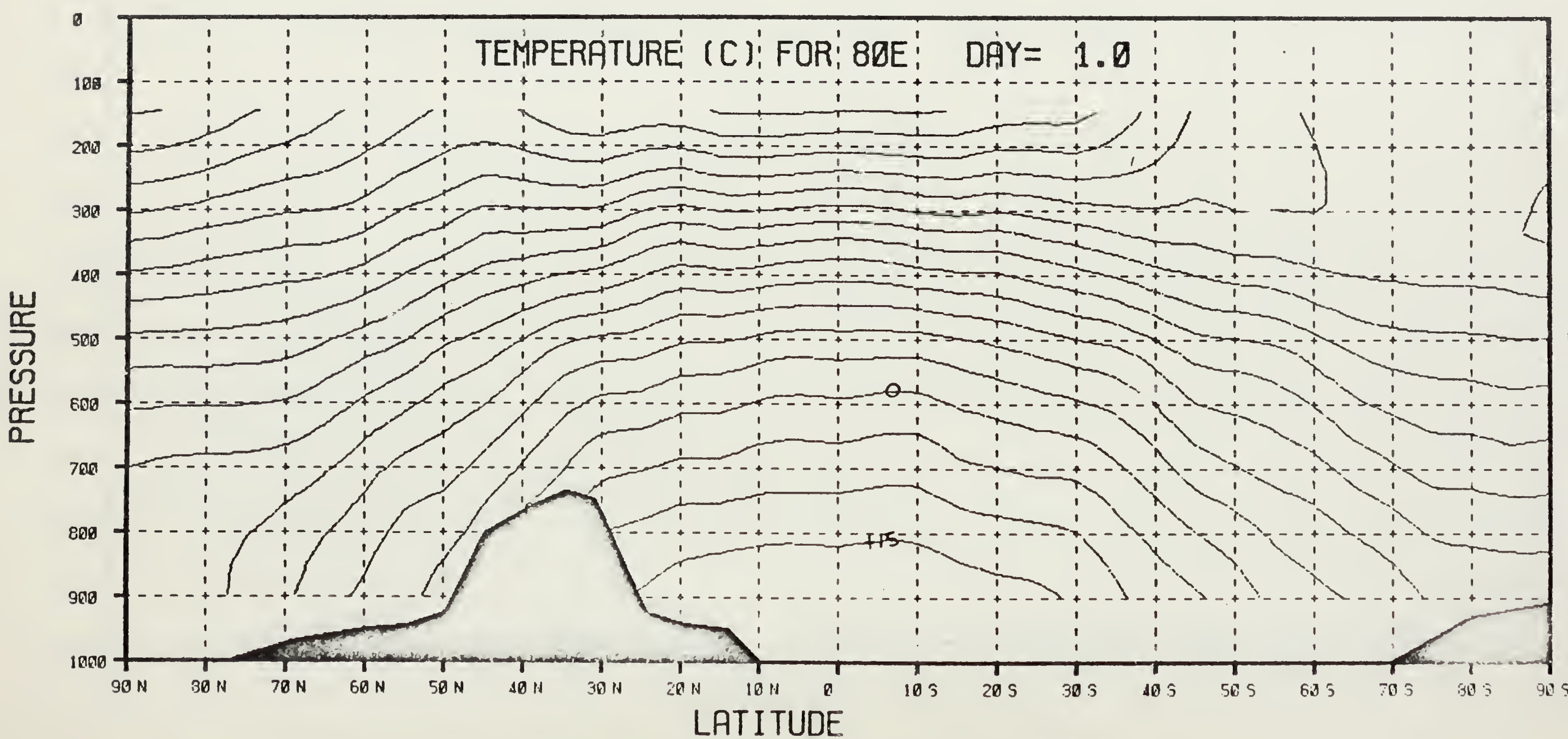

Figure 6a. Zonal temperature for day 1 (January)

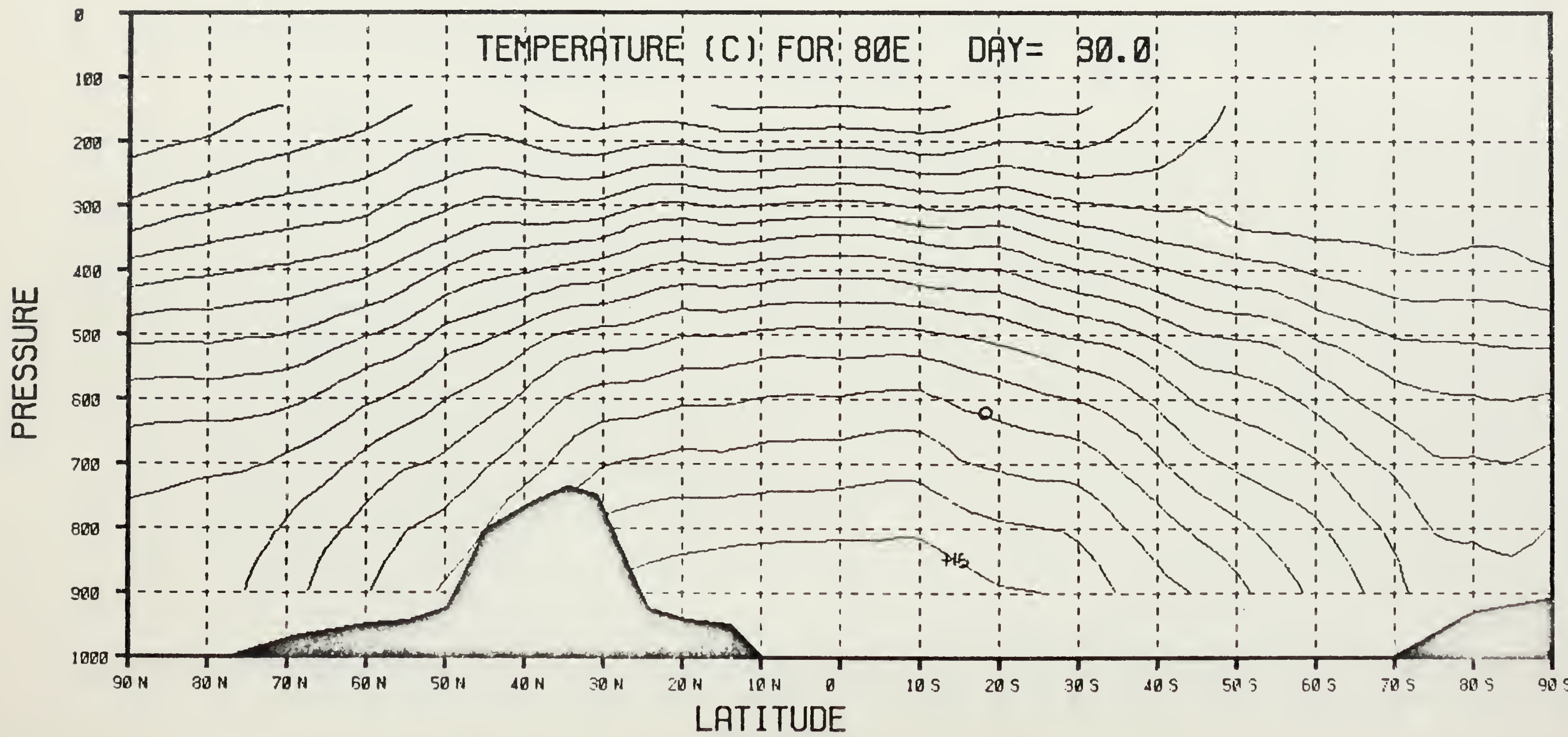

Figure 6b. Zonal temperature for day 30 (February)

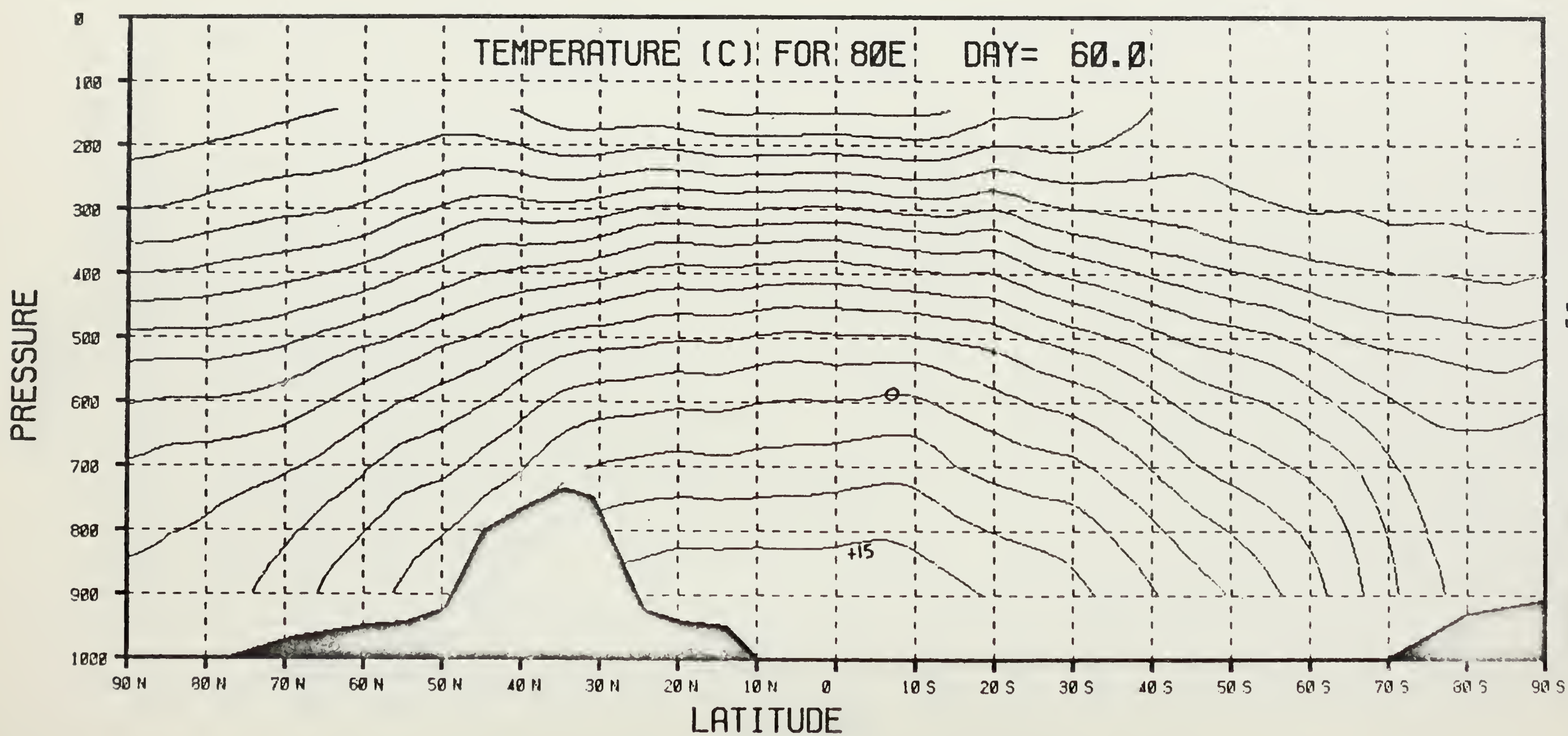

Figure 6c. Zonal temperature for day 60 (March)

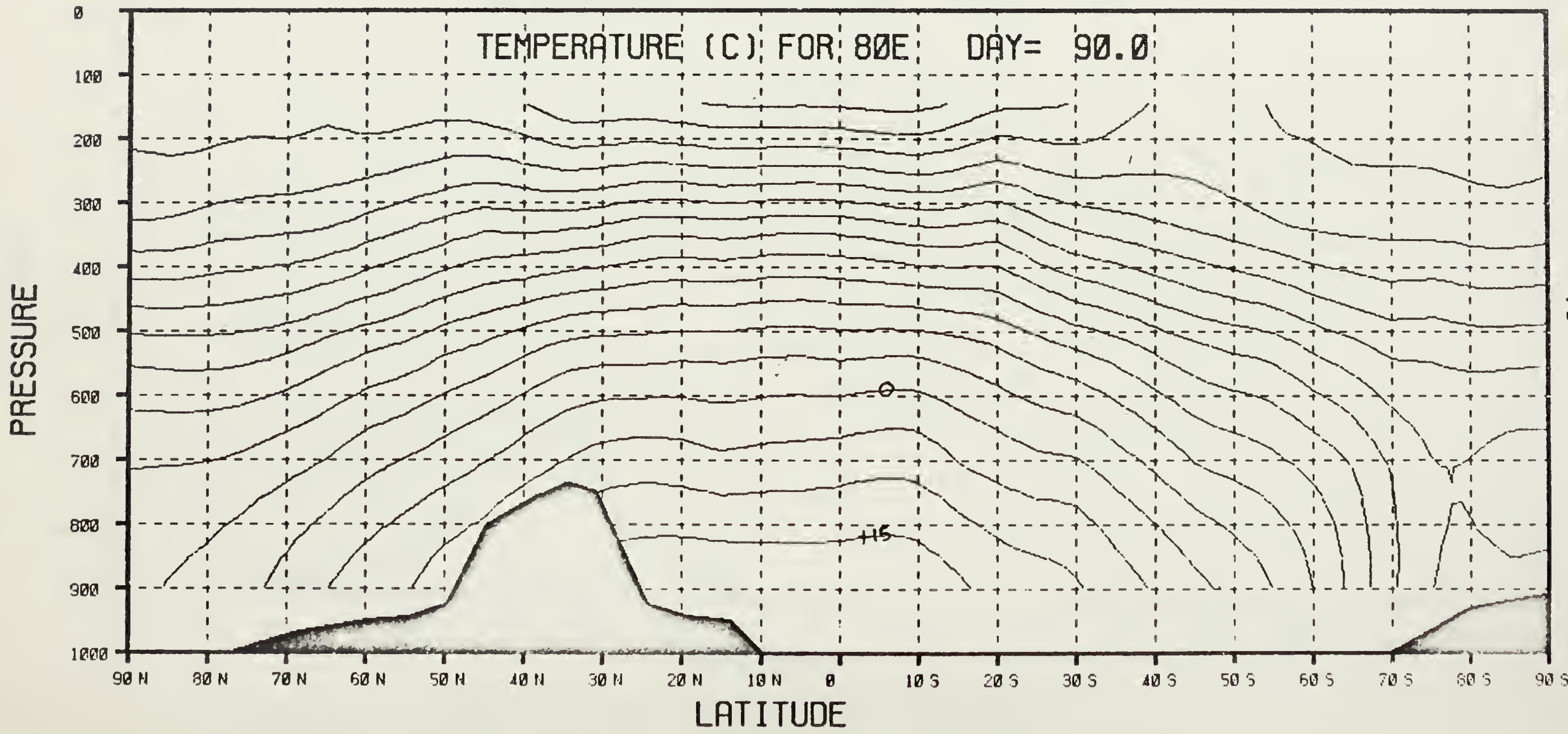

Figure 6d. Zonal temperature for day 90 (April)

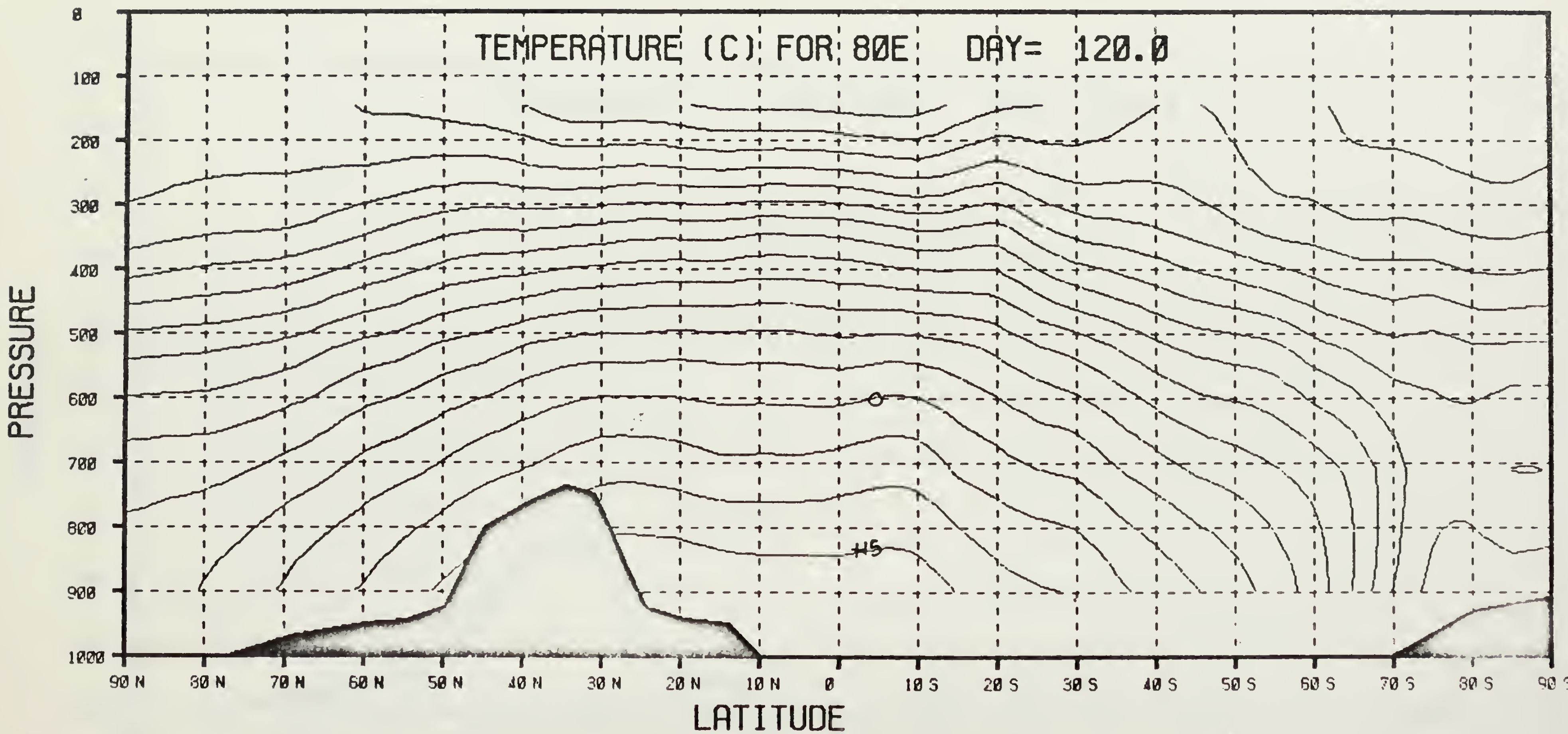

Figure 6e. Zonal temperature for day 120 (May)

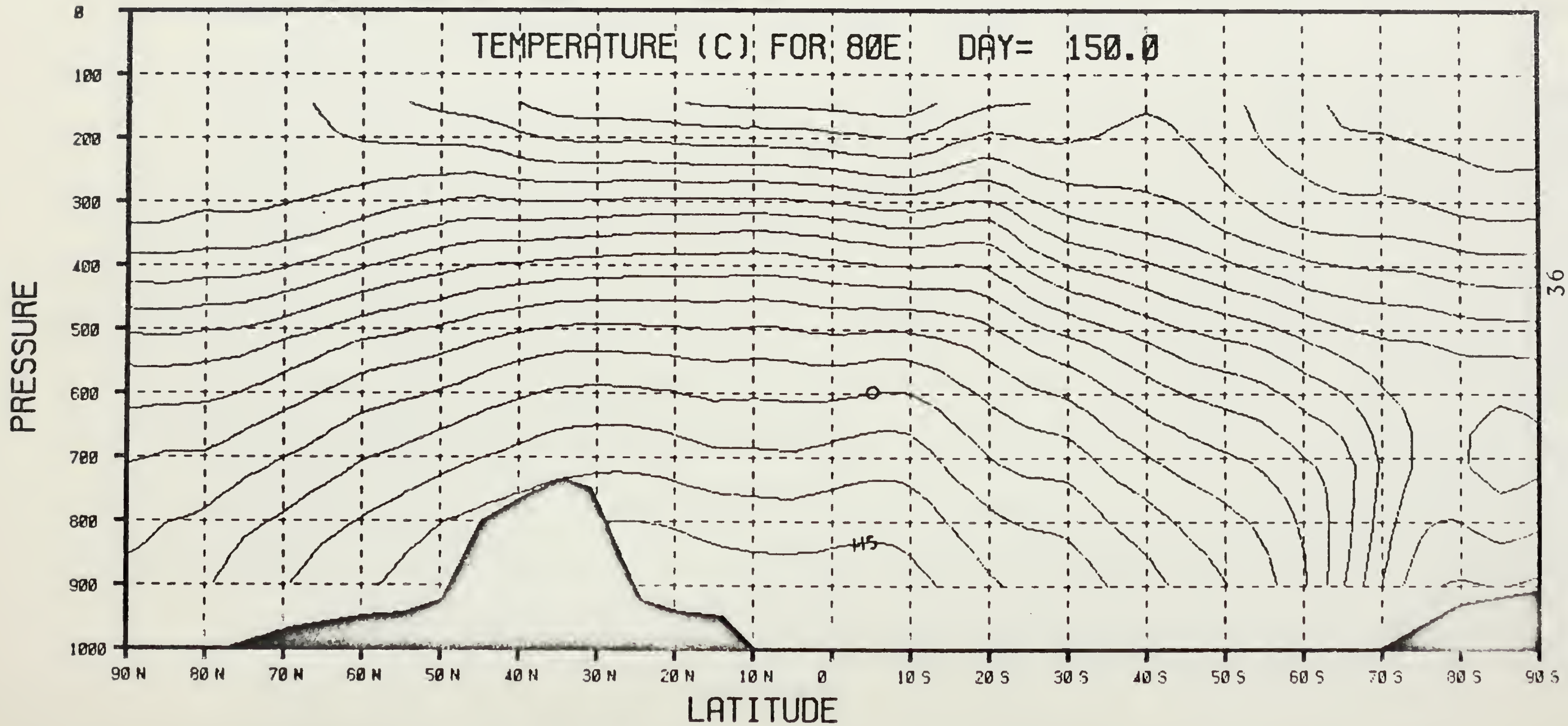

Figure 6f. Zonal temperature for day 150 (June)

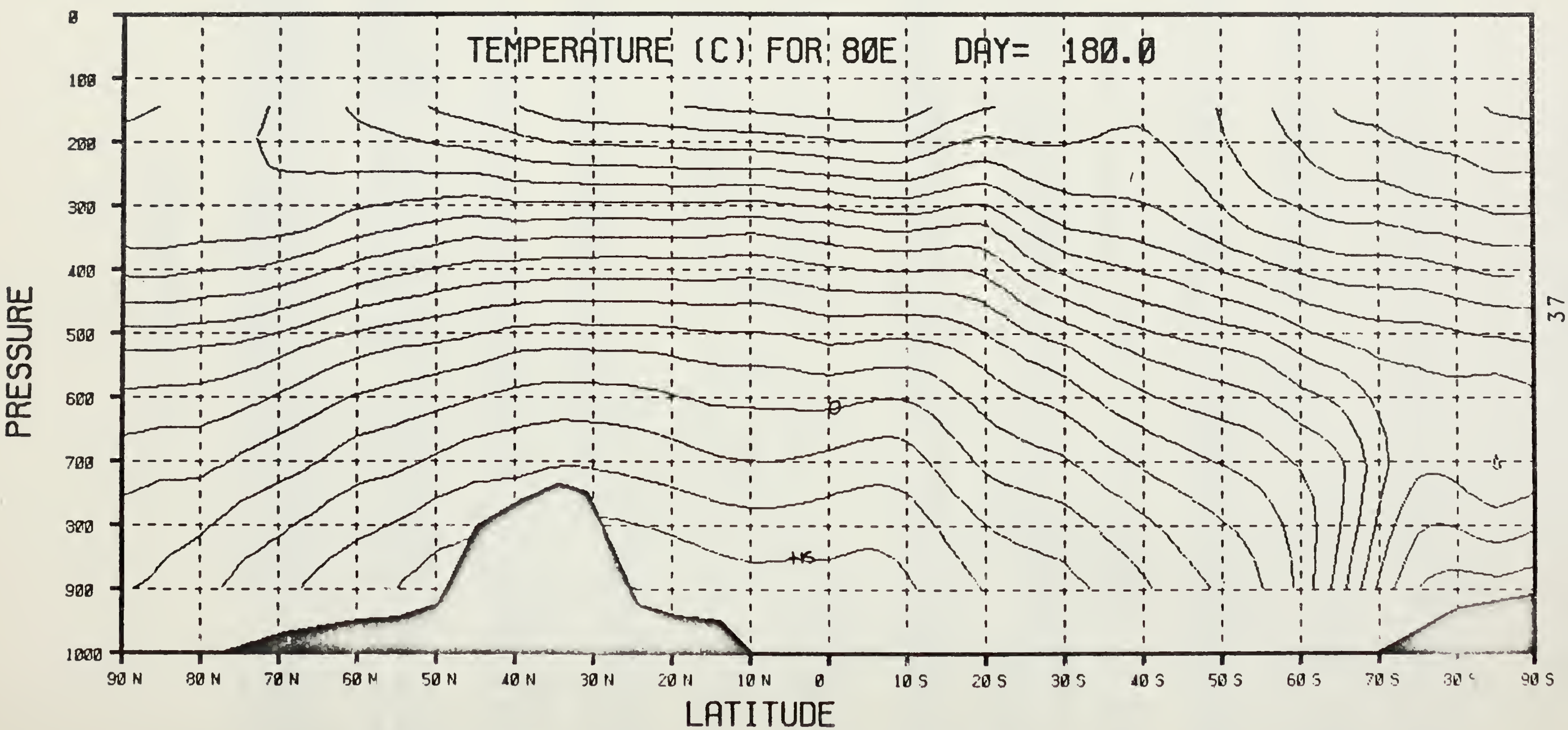

Figure 6g. Zonal temperature for day 180 (July)

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